AAS 19-436

APPROACH TO EXPLORING INTERSTELLAR OBJECTS AND LONG-PERIOD COMETS

Julie C. Castillo-Rogez,[*] Karen Meech,[†] Soon-Jo Chung[‡],

and Damon Landau, [§]

This paper aims to identify the best approaches for exploring planetary bodies with very long orbital periods, i.e., bodies that approach Earth only once in a lifetime. This includes long-period comets (LPCs), and the newly discovered classes of Manx comets and interstellar objects (ISOs). Long-period comets are high scientific value targets, as indicated in the current Planetary Science Decadal Survey. Interstellar objects open the fascinating possibility to sample exoplanetary systems. Manxes hold the key to resolving long-time questions about the early history of our solar system. Specific strategies need to be implemented in order to approach bodies whose orbital properties are at the same time extreme and unpredictable. As ground-based telescope capabilities are greatly improving, it will soon become possible to detect LPCs 10+ years before they reach perihelion. On the other hand, the smaller and/or non- or weakly active Manx comets and ISOs require reactive exploration strategies. Both types of bodies offer many challenges for close proximity observations that can be addressed by the deployment of multi-spacecraft architectures. We describe several concepts that leverage the many advantages offered by distributed sensors, fractionated payload, and various mother-daughter configurations to achieve high impact science within the reach of low-cost missions.

INTRODUCTION

This paper aims to identify the best strategies of using formation flying spacecraft for the in-depth exploration of planetary bodies with very long periods, i.e., bodies that cross our solar system and approach Earth only once in a lifetime. These bodies include Oort cloud comets (200+ years) and, now, interstellar objects, as there is no doubt the recently discovered ‘Oumuamua is not the first, and certainly not the last, interstellar visitor in our solar system. Long-period comets are the most primitive witnesses of the early solar system. Interstellar visitors are suggested to be ejecta from extrasolar planetary systems during the process of planet formation. Hence the scientific value

[*] Research Scientist, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109. Julie.C.Castillo@jpl.nasa.gov.
[†] Astronomer, Institute for Astronomy, University of Hawaii, HI 96822. meech@ifa.hawaii.edu.
[‡] Professor of Aerospace and Jet Propulsion Lab Research Scientist, California Institute of Technology, Pasadena, CA 91125. sjchung@caltech.edu.
[§] Systems Engineer, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109. Damon.Landau@jpl.nasa.gov

of exploring these objects is unbounded, even more so as a recent study suggested that these collisions could have offered a means to transfer life among extrasolar systems[1,2].

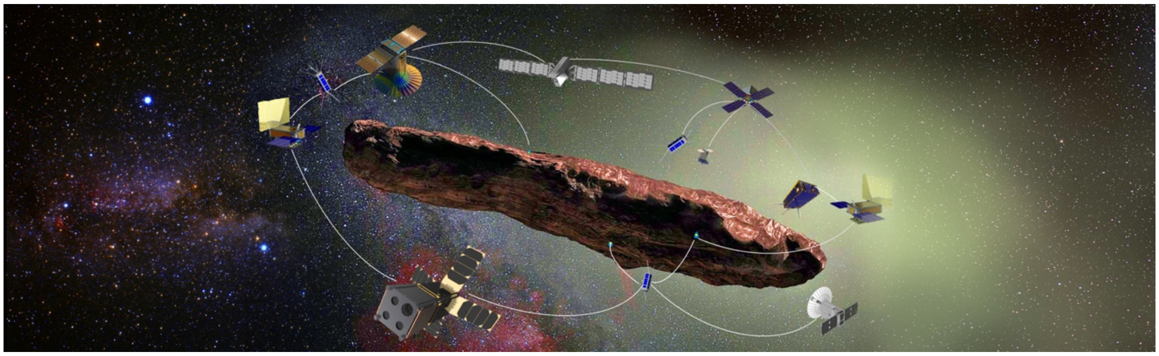

Figure 1. Notional concept of networked constellation investigating an interstellar object.

Challenges Offered by Long-Period Targets

The exploration of long-period objects is challenging for four main reasons: the orbital properties of these bodies are unknown in advance; they frequently have high inclinations; the encounter speeds are typically high (10s of km/s), hence the encounters may be very short; it may also be risky if the object ejects dust at high velocity. The only attempt to explore a long-period comet up close dates back to the encounter with Comet Halley in 1986. While Halley's period is only ~75 years, it is an important reference point for this study. Its visit was deemed such an important event that six spacecraft were sent by different space agencies: NASA, ESA, Roskosmos (USSR), and JAXA (its first space mission). The deployment of six spacecraft at once was and remains the first instance of the kind. The missions were mostly uncoordinated though and the projected science was only partially successful because the violence of the dense dust environment destroyed some of the instruments. We (collectively) do not know how to approach objects with velocities in excess of 50 km/s. The Halley comet missions, while bold, had a modest science return in comparison to the level of resources engaged. However, these missions were milestones that sparked the development of miniaturized instruments in Europe and Japan's line of science missions. Similarly, we expect that objects of major science significance like debris from extrasolar planetary systems and pristine building blocks of our solar system can foster novel approaches to space exploration and hopefully coordination among space agencies.

Premise of this Study

The challenges identified above may be addressed by sending a very large number of spacecraft by multiple space agencies, and in a coordinated manner. It is simply too big an endeavor to expect any single space agency to send a very large number of assets with a diversity of capabilities commensurate with the broad science knowledge sought at these bodies within current budgets. On the other hand, the enormous interest generated by the visits of long-period comets and 'Oumuamua on a worldwide scale indicates that an international effort to coordinate future exploration of these bodies is a worthy and realistic endeavor. Thirty years after the Halley comet missions, space programs around the globe have covered a lot of ground and new players are emerging (universities, developing countries) thanks to the rise of the CubeSats.

Indeed, constellations, formations, and swarms of small spacecraft have been identified as game changers for enabling new space science[3-6]. In recent times, there has been a tremendous development in regard to the technology maturation level achieved by small satellites (smallsats). This paper will explore how the many advantages offered by smallsats, and in particular of advanced distributed spacecraft architectures, can be used to address the above challenges and enable wholesome science investigations over a short observation window: e.g., coordination to synthesize a single, large, virtual instrument; innovative distributed measurement and data analysis techniques; emerging related technologies for CubeSats or smallsats (such as novel miniaturized instruments); autonomous operations; communication relay strategies; novel orbital organization approaches for constellations, or more effective swarming.

Paper Organization

This paper first reviews the science value and state of knowledge of long-period comets, Manx comets, and interstellar objects. Long-period comets have been long-time targets of interest, whereas Manx and ISOs are new objects. Hence, the science questions at the former are well established. Then we review the science definition based on the anticipated scope of future missions to each type of body. This leads to the definition of resource requirements and strawman payload for future missions. Then we develop the rationales for multi-spacecraft architectures and address the state of the art in key small spacecraft technologies.

STATE OF KNOWLEDGE

Long-Period Comets

Long-period comets come from the Oort Cloud, a region of the solar system at about 5000 to 100,000 a.u. It is believed to contain between 0.1 to 2 trillion comets. These are witnesses of the very early solar system and hold a record of the chemistry of the solar nebula at that time, as well as the contribution of presolar and interstellar sources. LPCs are mostly pristine since they have not been exposed repeatedly to high insolation, contrary to Jupiter Family Comets. This is illustrated by the much richer and denser comae found at LPCs[7]. LPCs show a wide range of orbital properties, characterized by varied inclinations (Figure 2). Their relative velocities to Earth may reach >70 km/s.

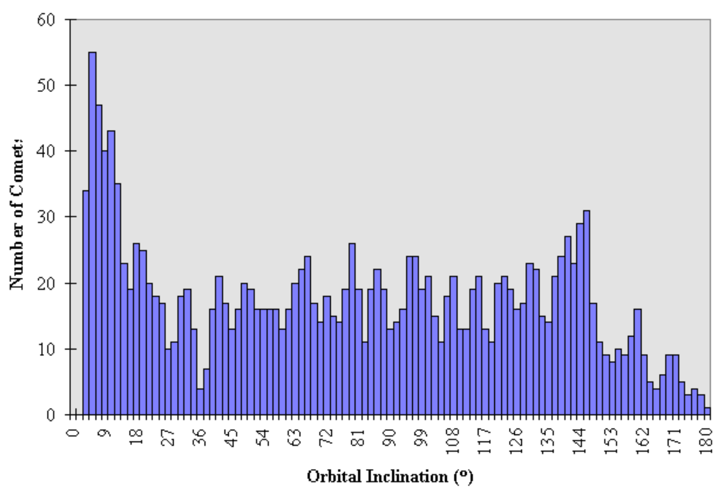

Figure 2 Orbital inclination distribution of observed long-period comets (pictures from Willman[21])

These targets present additional challenges due to their intensive gas and dust production if they are encountered near their perihelia. This requires heavily shielded spacecraft, as was done for the Giotto and CONTOUR missions[8,9]. In the case of Halley comet, the dust production was such that a single 1gm grain led to spinning the spacecraft. Meter-sized blocks are expected to be ejected like in the case of comet Hartley 2[10].

Manx Comets

The Manx comets are bodies that show the dynamical properties of comets – they come from the Oort Cloud – but exhibit little or no tail (like the Manx cats). They were first discovered by Meech et al.[11] who revealed their silicate nature. Meech et al. interpreted their existence as evidence for inner material ejected to the outskirt of the solar system, providing a test for early planetary migration models. Little is known about these objects whose sample is small. Their outgassing activity is 5-6 orders of magnitude less than other comets coming from the Oort Cloud and the lack of a tail is a challenge for detecting these bodies early enough for a rapid response mission.

Interstellar Objects

The first interstellar object 'Oumuamua was discovered in October 2017[1], which has led to significant interest from the community since. 'Oumuamua is a few 100 meters in size, has an albedo <0.1, and appears to be elongated with a 6:1 dimension ratio[12]. Faint outgassing has been suggested based on the anomalous orbit of 'Oumuamua on its outward orbit[13]. Various origins have been suggested for 'Oumuamua, including the infamous alien spacecraft idea. A more realistic scenario is that 'Oumuamua is a comet or leftover material from an exo-planetary system[14]. Hence the exploration of an object of this type can bring critical compositional constraints on another planetary systems. It has even been suggested that ISOs could be vectors of life transfer among planetary systems[2].

Constraints on the orbital properties of ISOs are limited to a single object right now. Englehardt et al.[15] suggested that at any given time, one ISO is present within 1 a.u., but simply too small to be detected. Owing to their expected small sizes and likely dark albedo, due to the extended exposure to space weathering, ISOs are hard to detect with sufficient lead time to launch a mission from Earth.

SCIENCE DEFINITION AND SCOPE OF FUTURE MISSIONS

The scope of future missions to long period objects depend on the class of these objects.

For observations of long-period comets, we follow the recommendations of the Planetary Science Decadal Survey[16]. The focus is on sampling volatiles for isotopic measurements in order to constrain the conditions in the early solar system. A sample return "a la Stardust" would be ideal but comes with major challenges. Material capture in aerogel was already complex in the case of Stardust and led to the loss of organics and the degradation of other fragile species (Brownlee et al.). Similarly, organics are significantly degraded, or even destroyed, for impacts at velocities >~6 km/s into mass spectrometers (MS). At the much faster velocities considered here, many compounds can react with the MS chamber, leading to fraught results[17]. On the other hand, dust spectroscopy is particularly suited for investigating the products of hypervelocity impacts. With an instrument such as SUDA or derivative, material destroyed upon impact is analyzed with a MS that yields elemental ratios, a wide array of isotopes, and organic functional groups[18]. Other observations, such as physical and rotational properties, dust and volatile coma density and structure, and nucleus properties are also of interest and can be achieved with visible and infrared imaging.

In the case of Manx comets, the key science goal is about confirming their inner solar system origin. This drives the measurement of their surface composition, which can be accomplished via infrared spectroscopy (near or mid-). The characterization of their volatile composition, via, for example UV spectroscopy, brings additional constraints on the accretional environment of these bodies. Physical and rotational properties are also sought. Density determination provides independent information on formation conditions and more generally on accretional processes in the early solar system.

In the case of ISOs, the extreme rare opportunity implies that a mission should be heavily instrumented to capture as much information as possible from these bodies. On the other hand, the lack of a priori knowledge of the properties of these bodies and the strong interest from the community and public for the in situ exploration of ISOs suggest that a small, easily launchable (e.g., smallsat) is also a valid consideration. ISOs are so new that a simple reconnaissance mission yielding physical, morphological, and first-order compositional properties would pave the way for more elaborate, follow-on missions. Characterizing the composition of the surface of a body exposed to the weathering of interstellar space would be of interest and requires spatial resolution sufficient (a few meters) to resolve fresh surface material overturned by small meteorites.

At non-active or weakly-active bodies, challenges such as low albedo and absence of a tail requires highly sensitive instruments and precludes the use of certain techniques (or drive the preferred use of certain techniques). For example, a likely low-density tail precludes the use of mass spectroscopy but could be detectable by UV spectroscopy that would at least provide an inventory of key volatile species. Alternatively, a mission may deploy an impactor, like Deep Impact, to eject materials ahead of a spacecraft equipped with mass and/or dust spectroscopy, and exposing a fresh surface for remote spectroscopy to investigate.

Density determination provides independent information on formation conditions. A low-density, i.e., highly porous body is representative of planetesimals, whereas a high-density, i.e., compact object would indicate the ISO is a fragment of a large and evolved object. Density measurements are challenging at small bodies (<1 km) and with a single flyby. They require a very close flyby (i.e., a few kilometers), which might be possible but requires autonomous navigation. In the case of very active bodies, small forces incurred by the interaction of gas with the spacecraft need to be accounted for. However, intense outgassing activity might just preclude close proximity measurement of this kind. Determination of thermal properties might be another way to poke at internal structure but these depend also on the extent of surface processing of the surface via interplanetary dust and ejecta production and condensation.

MISSION RESOURCE REQUIREMENTS

Two types of missions are envisioned. The first one assumes a spacecraft travels to the target and the other that the spacecraft is stationed in the Earth-Moon environment, or attached to the International Space Station or Lunar Gateway, and breaks out from that orbit to encounter an LPO. In the case of LPCs, early warning might be possible by detection with ground-based assets such as PANSTARRS 2. A good example is C/2017 K2, which was discovered in 2017[19]. Telescope archives allowed tracing the activity of that body back to 2013 when it was ~14 billion kilometers away. As telescopic observations progress, it should become easier to detect large LPCs 10+years away from their perihelia. In the meantime, the design of a reference mission that would be capable of returning compelling science should be considered even in the context of low-cost planetary mission programs and/or as part of the next planetary science decadal survey.

Considering that we will not know the paths of these "once-in-a-lifetime" objects until a few years before their perihelia, we created a fictitious population of objects in order to determine what percentage of these objects are accessible with current technology. For our fictitious population we assume a uniform distribution for comet approach directions (or direction of perihelion), B-plane angle (on solar approach to define inclination), and epoch of perihelion. We do not assume a distribution of perihelion distance, but instead sample a range from 0.5–1.5 a.u. and found little variation in percentage of accessible objects, with a slight preference for objects with perihelia near 1 a.u. The eccentricity is constrained to exactly 1 (parabolic). For each of these random objects we create a pork-chop plot with launch between 2-year prior to ½ year post perihelion and flight time between 0 and 10 years. The departure C_3 is capped at 150 km^2/s^2 and arrival speed (V_∞) is limited to 64 km/s. The pork-chop plots are created using Lambert fits (patched-conics) assuming a circular orbit for Earth. The data in Figure 3–Figure 9 represent 10,000 different comet orbits.

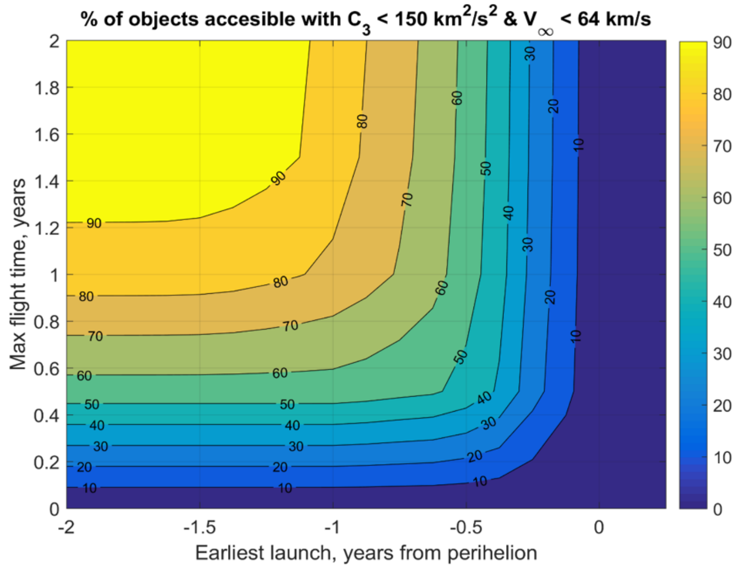

Figure 3 Percent of objects accessible with high launch energy and high encounter speed mapped to flight time and launch constraints.

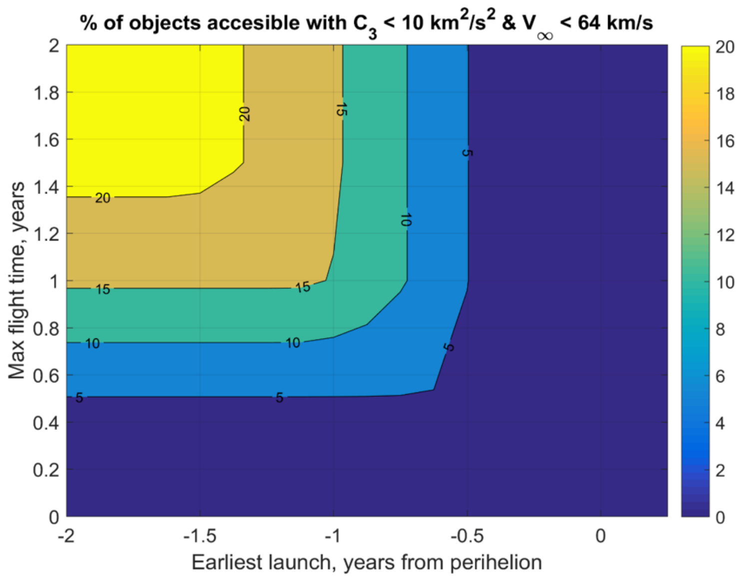

Figure 4 Percent of objects accessible with low launch energy and high encounter speed mapped to flight time and launch constraints.

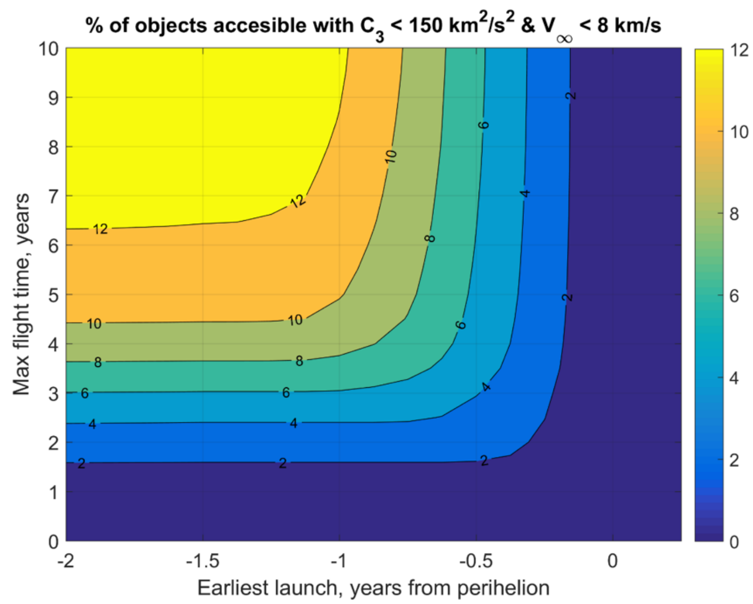

Figure 5 Percent of objects accessible with high launch energy and moderate encounter speed mapped to flight time and launch constraints.

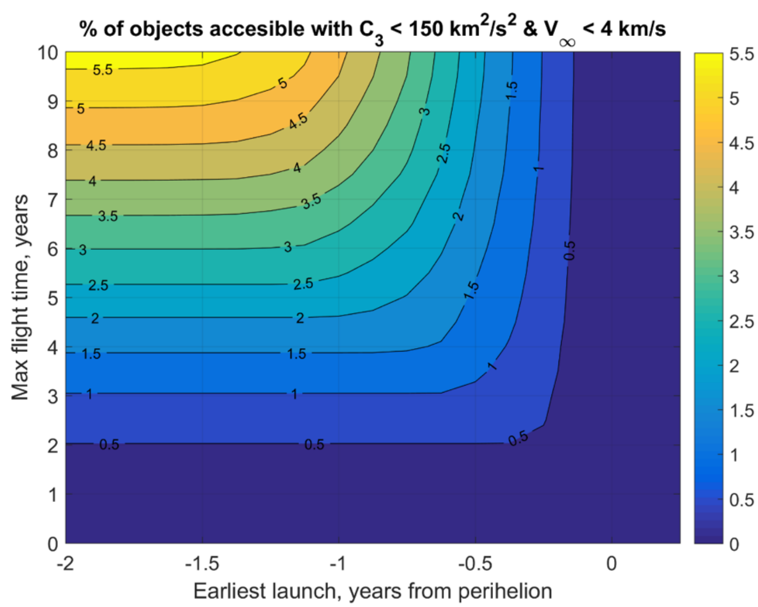

Figure 6 Percent of objects accessible with high launch energy and low encounter speed mapped to flight time and launch constraints.

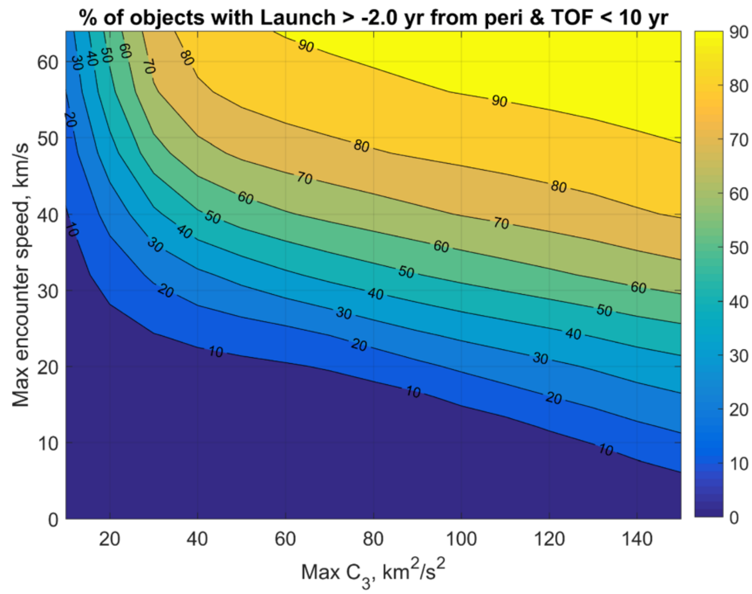

Figure 7 Trade space of encounter speed and launch energy with open bounds on launch date and flight time.

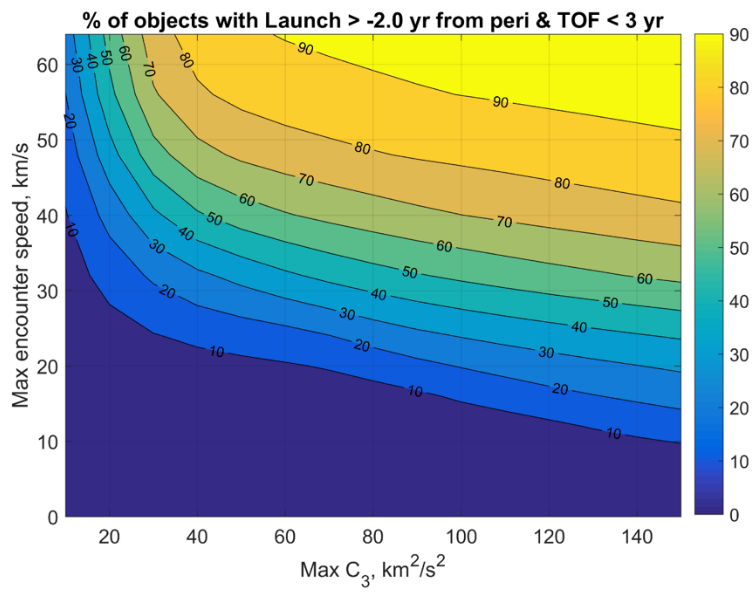

Figure 8 Trade space of encounter speed and launch energy with constrained flight time.

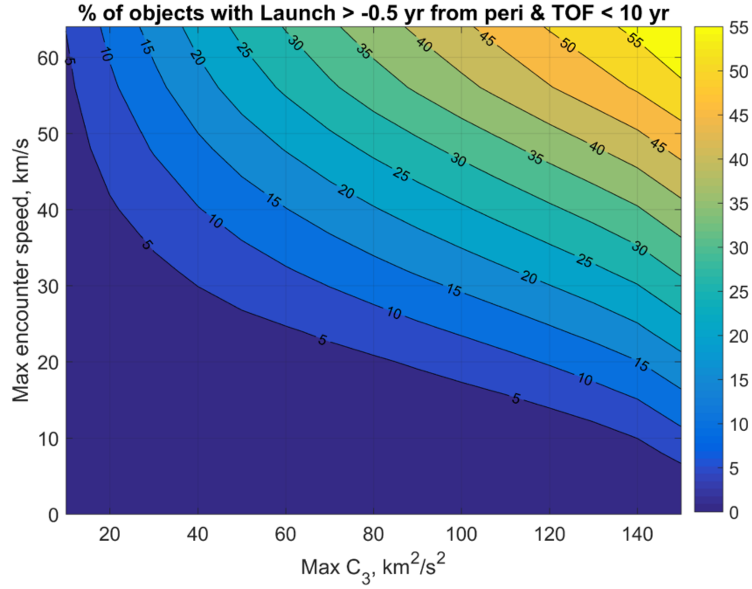

Figure 9 Trade space of encounter speed and launch energy with constrained launch date.

We also examined point designs of Jupiter-assisted transfers to long-period comets. These transfers provide a proof of concept for how Jupiter can be used to decrease approach velocity.

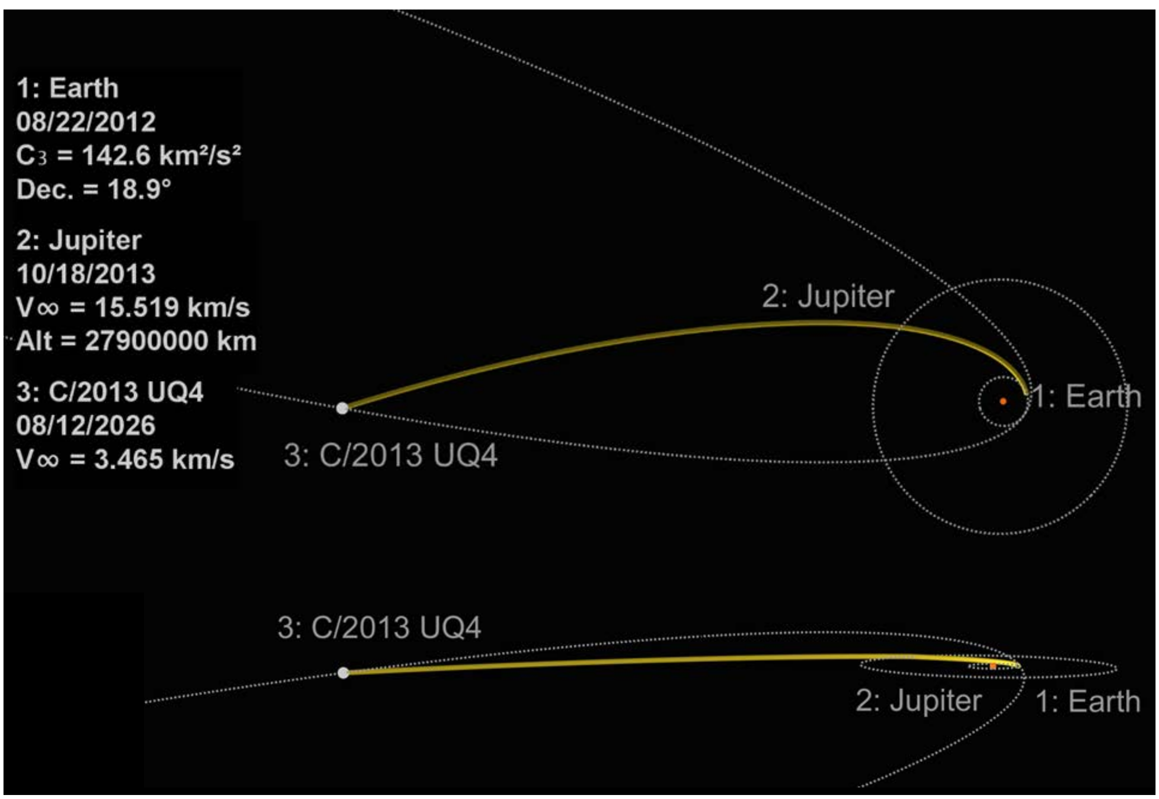

Figure 3 Direct transfer to C/2013 UQ4 (145° inclination) with 3.5 km/s arrival in 14.0 years.

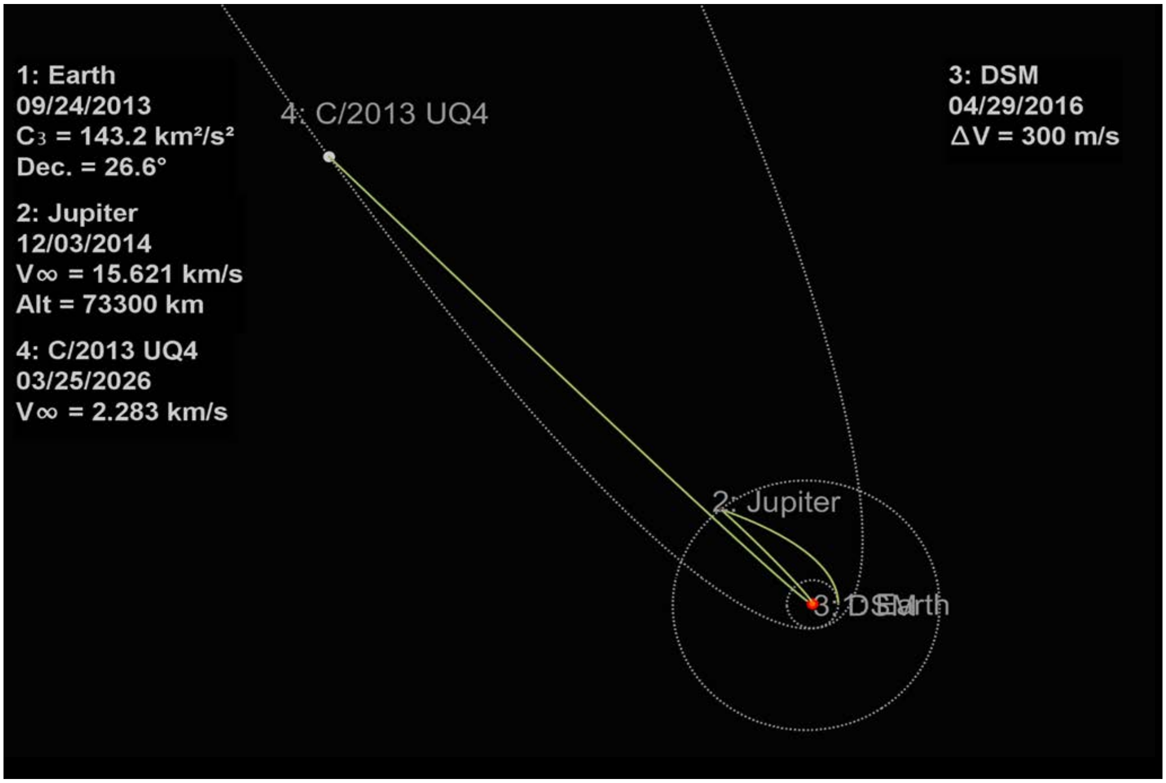

Figure 4 Retrograde transfer to C/2013 UQ4 (145° inclination) with 2.3 km/s arrival in 12.5 years.

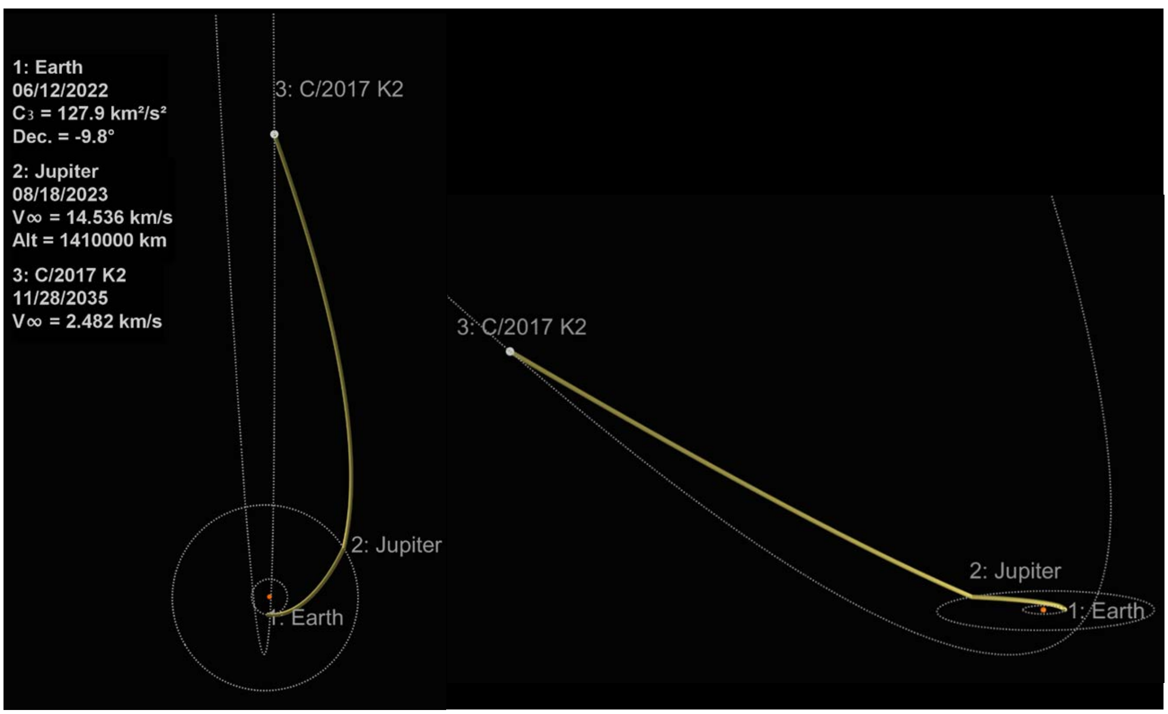

Figure 5 Transfer to C/2017 K2 (87° inclination) with 2.5 km/s arrival in 13.5 years.

ADVANTAGE OF MULTI-SPACECRAFT ARCHITECTURES

Multi-spacecraft architectures offer a multitude of advantages over monolithic spacecraft. These have already been explored in the literature[5,20] and are addressed here in light of the challenges offered by LPO exploration. A reference architecture would have a mothership acting as a telecom relay and carrier, deploy a variety of small spacecraft (hereafter referred to as "smallsat" without any assumption on their characteristics) while standing at a safe distance. The mothership maintains continuous or intermittent contact, depending on available power, with the smallsats performing various scientific tasks. The primary advantage of deploying multiple smallsats with the same instrumentation is to mitigate risk via block redundancy in order to guarantee science return. Multiple spacecraft also may be deployed with different vantage points. A smallsat may be a simple "dumb" mass impacting the target in order to generate a cloud of volatiles and dust sampled by a follow-on spacecraft while a third spacecraft observe and quantify the amount of ejected dust and a fourth one characterizes the composition of the newly generated fresh surface with remote sensing techniques.

Many experiments using distributed sensing with a given payload have been proposed in the literature[24]. That type of architecture is particularly well suited for fields and particles measurements in order to enable rapid characterization under multiple environmental conditions. Imaging under various vantage points enables complementary global, regional, and local observations of a given phenomenon, such as geological features or outgassing jets.

In order to optimize science operations, smallsat "scouts" may be released ahead of time to determine the main physical features of the target, in particular its shape and rotational properties. These would yield critical information for autonomous navigation at the target. This is best accomplished by observing under multiple vantage points, both to increase coverage in a relatively short observation time, but also to enable stereo-imaging and three-dimensional shape reconstruction (ref). Scouts can also probe the coma density to optimize sampling by a follow-on spacecraft.

Thanks to investments from many agencies over the past decade that also leverage significant advances in detectors and electronics pursued by industries, many science instruments have now reached resource requirements compatible with smallsat implementation. Small apertures (light or dust collection) remain a limitation that is in part compensated for by more sensitive detectors and the possibility for longer collection time with optimized concepts of operations. At this point in time, most types of instruments are in development or reaching infusion point. While the emergence of miniaturized instruments has been in part spurred by in situ exploration (of Mars, comet) and the growing interest for CubeSat-based deep space exploration, smallsats relax the constraints on instrument size and geometry and allow for deployable structures (e.g., large antennas for sounding radar). Power remains an issue, especially when observations rely on battery power only.

Intercommunication between smallsats is enabled by radio subsystems such as NASA's Elektra radio but remains limited to a few thousands of kilometers at most. This sets stringent constraints on the distribution of the multiple smallsats, especially considering the large velocities at play.

Guidance, Navigation, and Control and Autonomy

A key difference between formation flying and constellation, from the Guidance, Navigation, and Control (GNC) standpoint, is whether there exists any exchange of information to control relative motions of the spacecraft, which is true of formation flying architectures. If individual spacecraft are simply orbiting the target object without any coordination, the corresponding multi-spacecraft architecture is called a constellation, and often requires a reduced level of GNC technology challenges.

In order to accomplish either a fly-by or rendezvous mission with an ISO or LPC at a plausible distance from Earth (e.g., 3–10 a.u.), a combination of staged deployment and a Jupiter gravity-assisted transfer is essential. As for staged deployment and parking, multiple spacecraft, equipped with high ΔV, can be ready to be dispatched from a lunar parking orbit to a high-inclination target orbit once an LPO is identified from Earth-based or space-based telescopes. An autonomous navigation technology can be deployed to observe and construct a three-dimensional shape and topographical model of a target object without relying ground resources and direct communication with Earth. A conventional Stereo-photoclinometry (SPC) based optical navigation requires a lot of computational power and a human-in-the-loop landmark identification process that prevent on-board real-time autonomy. Multiple groups are looking into automating this 3D model construction and relative pose (position and attitude) estimation process using a monocular camera and on-board processing using feature-based incremental structure from motion techniques[22] or SLAM (simultaneous localization and mapping). Such autonomous navigation techniques will enable multi-spacecraft operation especially in close proximity to a target observation object.

If a rendezvous mission is possible, we can distribute multiple heterogeneous spacecraft over a comet using the swarm energy matching technique[23]. A real-time optimal trajectory planning and reconfiguration algorithm in the presence of nonlinear orbital motions has been derived and successfully tested with a large number of spacecraft models.[24-25] Mother-child spacecraft architectures can be developed especially to maneuver and land the distributed spacecraft and landers in the gravity well of a comet or ISO. An idea to capture and retrieve the dust chunks and debris flying off the surface using cubeset-based collectors that are tethered to the mothership can be explored. Tethered- or propulsion-based autonomous rendezvous and docking maneuvers between a mother-craft and child-craft has been studied in Foust et al. [26]

CONCLUSION

This preliminary work highlights the possibilities for exploring “once in a lifetime” targets, at least via flyby, despite the many challenges resulting from their intrinsic science value. Considering the significant relative velocities and, in the case of LPCs, the occurrence of a significant amount of dust, multi-spacecraft architectures involving a mothership and a heterogeneous constellation/fleet of CubeSats and/or smallsats enhance the chance of science success at relatively low cost. Science-grade, smallsat-sized instrumentation adequate for the science sought at the three classes of bodies is reaching maturation and infusion through programs like NASA’s SIMPLEx. A “Deep Impact”-style mission enabling the sampling of fresh dust and ejecta is an appealing feature for the Manx comets and ISOs. Autonomy and agile science software is an intrinsic component of these future concepts where the high relative velocities do not allow for closed loop operations.

ACKNOWLEDGMENTS

Part of this work is being carried out at the Jet Propulsion Laboratory, California Institute of Technology. This work is supported in part by the W.M. Keck Institute for Space Studies. K.J.M acknowledges support through NSF award AST-1617015 and support by the NASA SSO Near Earth Object Observations program 80NSSC18K0853. This study was initiated as part of a study hosted by the Keck Institute for Space Studies (KISS).

REFERENCES

[1] Meech, K.J., Weryk, R., Micheli, M., Kleyna, J.T., Hainaut, O.R., Jedicke, R., Wainscoat, R.J., Chambers, K.C., Keane, J.V., Petric, A., and Denneau, L., "*A brief visit from a red and extremely elongated interstellar asteroid*." *Nature*, doi:10.1038/nature25020, 2005.

[2] Berera A. "Space Dust Collisions as a Planetary Escape Mechanism. Astrobiology." doi:10.1089/ast.2017.1662, 2017.

[3] NRC report: Achieving Science with Cubesats: Thinking Inside the Box, http://www.nap.edu/23503, 2015.

[4] NRC Report:Powering Science: NASA's Large Strategic Science Missions, https://www.nap.edu/catalog/24857/

[5] *Small Spacecraft Technology State of the Art*, NASA/TP-2015-216648/Rev1, 2015.

[6] Bandyopadhyay, S., Foust, R., Subramanian, G. P., Chung, S. J., and Hadaegh, F. Y., "Review of Formation Flying and Constellation Missions Using Nanosatellites." *Journal of Spacecraft and Rockets*, Vol. 53, No . 3, May-June 2016.

[7] Mumma, M. J., DiSanti, M. A., Russo, N. D., Magee-Sauer, K., Gibb, E., and Novak, R. , "Remote infrared observations of parent volatiles in comets: A window on the early solar system." Icarus, Vol. 31, 2003, 2563-2575.

[8] Reinhard, R., "The Giotto encounter with comet Halley." Nature 321, 1986, 313-318.

[9] Osegueda, R. A., Carrasco, C. J., Orozco, M., Eftis, J., Reynolds, E., and Sholar, T. G., "Contour dust shield performance." Journal of Aerospace Engineering, Vol. 14, 2001, https://doi.org/10.1061/(ASCE)0893-1321(2001)14:4(147).

[10] A'Hearn, M.F., Belton, M.J., Delamere, W.A., Feaga, L.M., Hampton, D., Kissel, J., Klaasen, K.P., McFadden, L.A., Meech, K.J., Melosh, H.J., and Schultz, P.H., "EPOXI at Comet Hartley 2." *Science* 17 Jun 2011:Vol. 332, 2011. pp. 1396-1400.

[11] Meech, K.J., Yang, B., Kleyna, J., Hainaut, O.R., Berdyugina, S., Keane, J.V., Micheli, M., Morbidelli, A., and Wainscoat, R.J. "Inner solar system material discovered in the Oort cloud." S*cience Advances*, Vol. 2, e1600038.

[12] Jewitt, D., Luu, J., Rajagopal, J., Kotulla, R., Ridgway, S., Liu, W., and Augusteijn, T., "Interstellar Interloper 1I/2017 U1: Observations from the NOT and WIYN Telescopes." *The Astrophysical Journal Letters*, Vol. 850, L36.

[13] M Micheli, M., Farnocchia, D., Meech, K. J., *et al.* "Non-gravitational acceleration in the trajectory of 1I/2017 U1 ('Oumuamua)". Nature, Vol. 559, 2018, 223–226. doi:10.1038/s41586-018-0254-4.

[14] Raymond, S. N., Armitage, P. J., and Veras, D., "Interstellar Object 'Oumuamua as an Extinct Fragment of an Ejected Cometary Planetesimal." *Astrophysical Journal Letters*, Vol. 856, 2018, L7.

[15] Engelhardt, T., Jedicke, R., Vereš, P., Fitzsimmons, A., Denneau, L., Beshore, E., and Meinke, B., "An Observational Upper Limit on the Interstellar Number Density of Asteroids and Comets." Astrophysical Journal, Vol. 153, 2017, 133.

[16] National Research Council. *Vision and Voyages for Planetary Science in the Decade 2013-2022*. Washington, DC: The National Academies Press. https://doi.org/10.17226/13117. 2011.

[17] Jaramillo-Botero, A., An, Q., Cheng, M. J., Goddard III, W. A., Beegle, L. W., and Hodyss, R., "Hypervelocity Impact Effect of Molecules from Enceladus' Plume and Titan's Upper Atmosphere on NASA's Cassini Spectrometer from Reactive Dynamics Simulation." *Physical Review Letters*, Vol. 109, 2012, id. 213201.

[18] Horanyi, M. et al., "Fragments from the Origins of the Solar System and our Interstellar Locale (FOSSIL): A Cometary, Asteroidal, and Interstellar Dust Mission Concept." *IEEE Aerospace Conference* Proceeding, 2019.

[19] Hui, M. T., Jewitt, D., and Clark, D., "Pre-discovery Observations and Orbit of Comet C/2017 K2 (PANSTARRS)." *Astronominal Journal*, Vol. 155, 2017, 25.

[20] Baker, J., Vane, G., Bousquet, P., "Planetary Science Enabled by the New Generation of SmallSats and Miniaturized Scientific Instruments." Report of the International Academy of Astronautics, 2017.

[21] Willman Jr, A. J. "Implications of Magnitude Distribution Comparisons between Trans-Neptunian Objects and Comets," http://www.princeton.edu/~willman/tno-comet/tnocomet.pdf

[22] F. Baldini, A. Harvard, S.-J. Chung, I. Nesnas, and S. Bhaskaran, "Autonomous Small Body Mapping and Spacecraft Navigation," Proc. 69th International Astronautical Congress, Bremen, Germany, 1 – 5 October 2018.

[23] D. Morgan, S.-J. Chung, L. Blackmore, B. Acikmese, D. Bayard, and F. Y. Hadaegh, "Swarm-Keeping Strategies for Spacecraft under J2 and Atmospheric Drag Perturbations," Journal of Guidance, Control, and Dynamics, vol. 35, no. 5, September-October 2012, pp. 1492-1506.

[24] D. Morgan, S.-J. Chung, and F. Y. Hadaegh, "Model Predictive Control of Swarms of Spacecraft Using Sequential Convex Programming," Journal of Guidance, Control, and Dynamics, vol. 37, no. 6, 2014, pp. 1725-1740.

[25] D. Morgan, G. P. Subramanian, S.-J. Chung, and F. Y. Hadaegh, "Swarm Assignment and Trajectory Optimization Using Variable-Swarm, Distributed Auction Assignment and Sequential Convex Programming," The International Journal of Robotics Research, vol. 35, no. 10, September 2016, pp. 1261–1285.

[26] R. C. Foust, Y. K. Nakka, A. Saxena, S.-J. Chung, and F. Y. Hadaegh, "Automated Rendezvous and Docking Using Tethered Formation Flight," Proc. 9th International Workshop on Satellite Constellations and Formation Flying (IWSCFF), Boulder, Colorado, June 19-21, 2017.